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Blazar Compton efficiencies: *Fermi*, external photons and the Sequence

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ABSTRACT
The *Fermi*-LAT survey provides a large sample of blazars selected on the strength of their inverse Compton emission. We cross-correlate the first *Fermi*-LAT catalogue with the CRATES radio catalogue and use this sample to investigate whether blazar gamma-ray luminosities are influenced by the availability of external photons to be up-scattered. Using the 8.4 GHz flux densities of their compact radio cores as a proxy for their jet power, we calculate their Compton Efficiency parameters, which measure the ability of jets to convert power in the form of ultra-relativistic electrons into Compton gamma-rays. We find no clear differences in Compton efficiencies between BL Lac objects and FSRQs and no anti-correlation between Compton efficiency and synchrotron peak frequency. This suggests that the scattering of external photons is energetically unimportant compared to the synchrotron self-Compton process. These results contradict the predictions of the blazar sequence.

Key words: Galaxies – Active galaxies – blazars.

1 INTRODUCTION

Some active galaxies produce relativistic jets from their nuclei and, when the angle to the line of sight is small, the resulting Doppler boosting is such that the non-thermal emission from the jets can dominate the observed luminosity from radio through to gamma-ray wavelengths. Collectively, such objects are labelled “blazars”. At radio, X-ray and gamma-ray wavelengths these are amongst the brightest objects in the extragalactic sky (for a review of radio-loud active galactic nuclei see Urry & Padovani 1995).

Blazars can be split into two types: flat spectrum radio quasars (FSRQs) and BL Lac objects, though the boundaries between BL Lacs and FSRQs can sometimes be a bit blurred (e.g. Vermeulen et al. 1995). The main observational difference between the two types of blazar lies in their optical spectra; FSRQs show strong broad emission lines, with continuum emission usually (but not invariably) dominated by thermal emission believed to be from an accretion disk, while BL Lacs lack strong emission lines and have smooth optical continuum spectra believed to be of non-thermal origin. Therefore, BL Lacs and FSRQs have large differences in their thermal to non-thermal luminosity ratios. As a consequence, there is a large variation in the availability of photons originating from regions external from the jet that can be Compton scattered.

The spectral energy distributions (SEDs) of blazars are characterised by emission produced by two different mechanisms, which results in a distinct two-peak shape in log space. At longer wavelengths, blazar non-thermal spectra are dominated by synchrotron emission from ultra-relativistic electrons spiralling in the jet magnetic field. At the shorter wavelengths the dominant emission process is thought to be inverse Compton scattering of low-energy photons by the same synchrotron electrons (Konigl 1981; Dermer & Schlickeiser 1993; Fossati et al. 1998). Both emission mechanisms will reduce the energy of the relativistic electrons. The highest energy electrons will radiate away most of their energy either by the synchrotron or inverse Compton mechanisms, depending upon which has the greater energy density: the magnetic field in the jet or the low-energy photons. In the compact regions at the base of the jets the inverse Compton mechanism will dominate and this is where the gamma-ray emission from blazars that has been detected in abundance by the *Fermi* gamma-ray space telescope is thought to originate.

The seed photons for the inverse Compton emission can be produced internally within the jet, and/or be the external AGN photons. The radiation produced is referred to as synchrotron self-Compton (SSC) and external Compton respectively (e.g. Ghisellini & Taveccio 2008). It has been proposed that the relative strength of external Compton emission compared to SSC emission can explain the diversity in the spectral energy distributions of blazars, and can give rise to the “blazar sequence” (Fossati et al. 1998; Ghisellini et al. 1998; Ghisellini & Taveccio 2008; Sambruna et al. 2009).

2 BLAZAR SEQUENCE

For more than a decade there has been extensive discussion focused on the blazar sequence and the relative importance of external and internally-generated photons in the inverse Compton pro-

cess (e.g. Padovani et al. 2007). The blazar sequence was originally presented in two parts: a phenomenological aspect concerning an observed anti-correlation between synchrotron peak frequency and radio luminosity (Fossati et al. 1998), and a theoretical counterpart primarily concerning the abundance of external photons that can be inverse Compton scattered (Ghisellini et al. 1998). More recently the sequence framework has been extended to incorporate black hole mass and accretion rate (Ghisellini & Taveccio 2008) but we will focus exclusively on the role of external photons here.

The theoretical argument concerning external photons is that there will be a cut-off in the energy spectrum of the synchrotron electrons, and hence a frequency-dependent cut-off in the synchrotron emission. The addition of external photons to scatter the most energetic electrons should therefore decrease the frequency of the cut-off. The presence of AGN disk and/or broad line emission in FSRQs indicates that there are copious external photons available for scattering. However, BL Lac spectra show no evidence for an external source of photons associated with AGN emission. The primary contention of the blazar sequence is that the more external photons there are, the lower the expected peak frequencies of a blazar SED. This expected trend is seen between FSRQs and BL Lacs. This has been interpreted in different ways; either as strong observational evidence supporting the blazar sequence (e.g. Fossati et al. 1998; Ghisellini & Taveccio 2008) or as a clear indication that BL Lacs and FSRQs comprise physically distinct populations of objects (e.g. Anton & Browne 2005; also see Padovani et al. 2007 for a review). FSRQs generally have higher radio luminosities than BL Lacs, thus a connection can be made between the theoretical argument and the apparent anti-correlation between radio luminosity and synchrotron peak frequency.

Though the phenomenological aspect of blazar sequence may be controversial, there is little doubt that external Compton photons are required to explain some of the individual SEDs in FSRQs, for example in 3C454.3 (Bonnoli et al. 2010).

It is important to remember that, in the active galaxies that produce relativistic jets, only a small proportion of the bulk kinetic energy in the outflow is converted into ultra-relativistic electrons. These electrons in turn produce the electromagnetic signatures that enable us to identify them. Though it is the product of the highest energy electrons that dominate the electromagnetic spectrum, most of the energy in the form of these synchrotron electrons is stored amongst the lower energy electrons, not those with the highest energies. A key issue, that is partially addressed by the blazar sequence discussion, is what gives rise to the wide range of synchrotron peak frequencies (which are indicative of the maximum energies of the synchrotron electrons) in objects with apparently similar jet energies.

3 COMPTON EFFICIENCY

We introduce a simple concept of "Compton efficiency", which is a measure of how efficiently power in the form of ultra-relativistic electrons in a jet is converted by the inverse Compton process into gamma-ray luminosity. In the following we will assume that all gamma-rays are produced by inverse Compton scattering and ignore non-leptonic processes (e.g. Mücke et al. 2003).

In the case of a jet whose energy losses are initially dominated by SSC, as the external photon field is increased two things will happen: the synchrotron peak frequency will decrease, and the integrated gamma-ray luminosity will increase. However, the low frequency (radio) synchrotron emission will remain unchanged. This

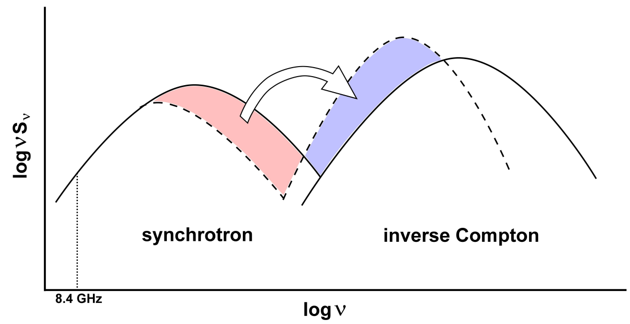

Figure 1. Cartoon of blazar spectral energy distributions, illustrating the key ideas of this paper. The solid SED represents a blazar with no external photons. When a source of external photons is introduced, energy from the synchrotron regime (left pink shaded area) is transferred to the inverse Compton SED (right blue shaded area). The resulting dashed SED has lower peak frequencies and higher inverse Compton peak emission, but the low frequency radio emission is unaffected.

is illustrated in Figure 1 in terms of changes to the spectral energy distribution caused by the presence of external photons. Because the radio emission is immune to the energy loss processes which only affect the highest energy electrons, we can use the radio emission as a proxy for the energy content of the jet in the form of relativistic electrons. Therefore to quantify the impact of the external photon field, we use the ratio of the gamma-ray emission at the inverse Compton (high frequency) peak of the SED to the compact nuclear radio emission as a measure of the inverse Compton efficiency ϵ, i.e

$$\epsilon = \log_{10} \frac{(\nu S_\nu)_{\rm IC,\ peak}}{(\nu S_\nu)_{\rm GHz}}. \quad (1)$$

The choice of the best measure of the gamma-ray emission required careful consideration. We adopt $(\nu S_\nu)_{\rm IC,\ peak}$, where $\nu_{\rm IC,\ peak}$ and $S_{\nu_{\rm IC,\ peak}}$ are the frequency and the flux density at which the inverse Compton SED peaks respectively. We do this because we are trying to measure an energy efficiency and the peak in the SED measures the maximum energy output. We cannot simply use the measured gamma-ray flux density as a proxy because the different types of blazar have a wide range of, and systematically different, inverse Compton peak frequencies (Abdo et al. 2009, 2010b). Implicit in our definition of Compton efficiency is the assumption that both the radio and gamma-ray emission have the same degree of relativistic beaming and hence taking the ratio of observed luminosities cancels the effects of different Doppler factors in different objects.

Our objective is to look for correlations of Compton efficiencies with other observables. Most blazar samples are selected in the radio or the X-ray and therefore contain objects selected by their synchrotron emission, or a combination of synchrotron and inverse Compton emission. However, a gamma-ray selected sample of blazars will be selected purely by their inverse Compton emission. Thus, with such a sample, we can safely compare the Compton efficiencies of different types of object.

4 *Fermi*-LAT SURVEY AND OTHER DATA

4.1 Input data

The first *Fermi*-LAT (Large Area Telescope) catalogue (1FGL) contains 1451 sources detected in the 0.1–100 GeV energy

range during the first 11 months of science observations with *Fermi* (Abdo et al. 2010b). We use the online *Fermi*-LAT point source catalogue[1] to cross-correlate these sources with those listed in the Combined Radio All-Sky Targeted Eight GHz Survey (CRATES) compilation of compact flat spectrum radio sources (Healey et al. 2007). The CRATES catalogue excludes objects less than 10 degrees from the Galactic plane to avoid contamination by Galactic radio sources. This gives us a parent sample of 1043 *Fermi*-LAT sources. We will work with two subsamples: the FSRQs and the BL Lacs (as classified by 1FGL) of which there are 271 and 288 respectively. When this sample is cross-correlated with the CRATES catalogue, we obtain 224 FSRQs and 167 BL Lacs. The lower number of BL Lac correlations is likely due to the different flux density limits of FSRQs and BL Lacs in the 1FGL classification process, and the constant flux density limit within the CRATES catalogue.

We choose to use the 8.4 GHz flux density measurements from CRATES in our Compton efficiency calculation because this frequency provides a balance between probing the jet power and obtaining high enough angular resolution to separate the core (jet) emission from any extended emission. In particular, it combines high-resolution 8.4 GHz observations from the VLA in the northern hemisphere (predominantly from the Cosmic Lens All-Sky Survey, CLASS; Myers et al. 2003; Browne et al. 2003) with similar observations from ATCA in the southern hemisphere (predominantly from the AT20G survey, Ricci et al. 2004; Sadler et al. 2006). However, a disadvantage of the CRATES catalogue is that it lists each part of multi-component sources separately. While the majority of multi-component sources have an obvious dominant component that we take as the core, in some cases the core position and flux density are not obvious. Since we use the 8.4 GHz flux densities in our efficiency calculations, we have examined the radio data for each source carefully to make sure that we are using the correct value for the core radio emission. In two cases (1FGL J0856.6+2103 and 1FGL J2149.7+0327) we have rejected the object from our sample because we were uncertain about which of two radio components were associated with the gamma-ray objects. An issue with the radio measurements is that most were made a decade before the gamma-ray observations, so radio variability will introduce an extra scatter in any measurement of Compton efficiency; we will discuss the effects of this in Section 6.1.

4.2 Gamma-ray peak

As stated above, choosing the optimum gamma-ray quantity to use in the definition of the Compton efficiency is important and we believe that the value of νS_ν at the inverse Compton peak of the SED is the best available. As such, we need to estimate the value of νS_ν from the existing data. We use the recipe given by Abdo et al. (2010b) to estimate the inverse Compton peak frequency of an SED given the measured photon index (which they also provide). Abdo et al. (2010b) also list gamma-ray flux densities in 6 bands in the 0.03–100 GeV range; we use the 0.1–0.3, 0.3–1, 1–3 and 3–10 GeV fluxes as the majority of our sources only have an upper limit quoted in the lowest and highest energy bands.

Estimating the flux density at the peak frequency is easy when the peak lies within the *Fermi* energy range; we use two different methods to calculate the peak flux density when this is not the case. If there are sufficient flux density measurements, we use these

[1] `http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilpsc.html`

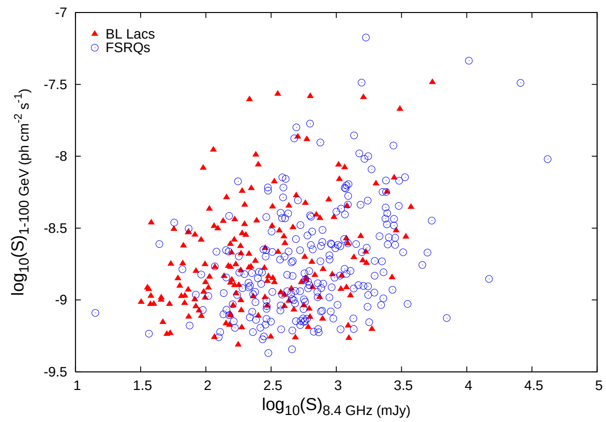

Figure 2. CRATES 8.4 GHz flux density against *Fermi* 1–100 GeV flux showing a weak correlation. BL Lacs are shown by red filled triangles, and FSRQs are shown by blue unfilled circles.

with the estimated peak frequency to fit a symmetric parabola. In cases where there are insufficient flux densities, we make the additional assumption that blazar SEDs have a characteristic width at a given vertical distance from the peak. Using the 238 blazars that we can fit a parabola to, we measure the width of the parabola at $\log(\nu S_\nu) = \log(\nu S_\nu)_{\mathrm{IC,\ peak}} - 1$ and find blazars have a median SED width $\Delta \log \nu_{\mathrm{Hz}} = 5.5$ (with a standard deviation of 1.39). This value is used to iteratively fit a parabola to those sources with insufficient flux measurements. The parabola is then used to calculate the gamma-ray peak flux density.

5 RESULTS

5.1 2-colour plots

In Figure 2 we show a plot of the 1–100 GeV flux, as detected by *Fermi*-LAT, against the 8.4 GHz flux density from CRATES. Similar plots have been shown in e.g. Abdo et al. (2010b); Ghirlanda et al. (2010); Peel et al. (2011), but we repeat the plot here for comparison. Two things are obvious from Figure 2: BL Lacs and FSRQs occupy overlapping but distinguishable areas and there is a correlation between the gamma-ray and radio flux densities. From this plot there is also an indication that for a given gamma-ray flux BL Lacs have on average somewhat lower radio flux densities. This would hint that BL Lacs might even have slightly higher Compton efficiencies than FSRQs (in opposition to the expectations of the original blazar sequence) but it could also arise from subtleties of the identification process used by Abdo et al. (2010b).

The top panel of Figure 3 shows νS_ν at the inverse Compton peak against the 8.4 GHz flux density (multiplied by ν for consistency). This plot shows many of the same qualitative features as Figure 2. There is still an indication that, if anything, the BL Lac objects have on average less radio luminosity for a given gamma-ray luminosity than the FSRQs. It is also noticeable that the correlation between the quantities is stronger (Spearman rank correlation coefficient $\rho = 0.534$ for Figure 3, top panel, compared to $\rho = 0.293$ in Figure 2) giving us encouragement that using the gamma-ray peak νS_ν rather than the flux in a single band has eliminated some of the bias due to the wide spread in peak frequencies.

In order to see how sensitive the results are to the exact method used to determine the gamma-ray peak frequencies, in the bottom

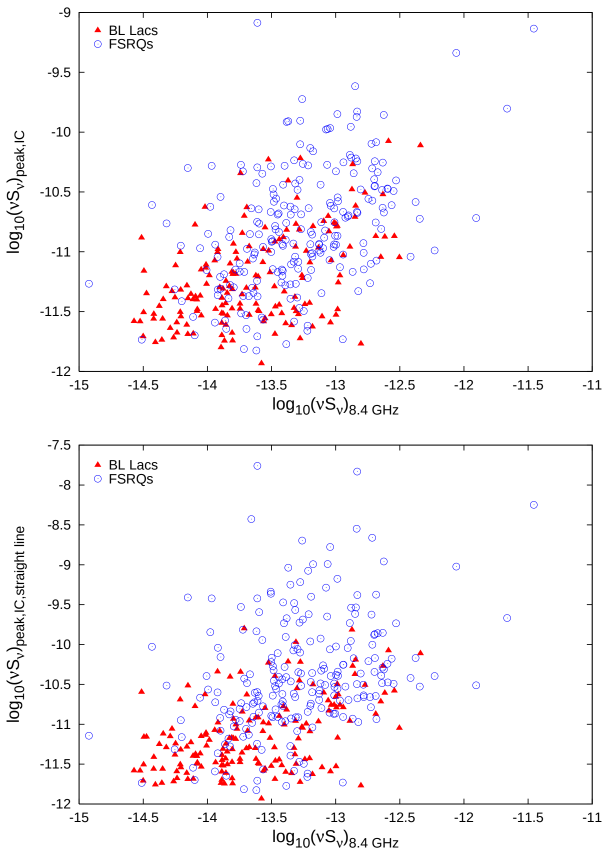

Figure 3. Top: 8.4 GHz radio flux density (multiplied by ν for consistency) against νS_ν at the peak of the inverse Compton SED regime showing a correlation. BL Lacs are shown by red filled triangles, and FSRQs are shown by blue unfilled circles. **Bottom:** As top panel but with $\nu S_{\nu_{peak}}$ determined by a linear fit.

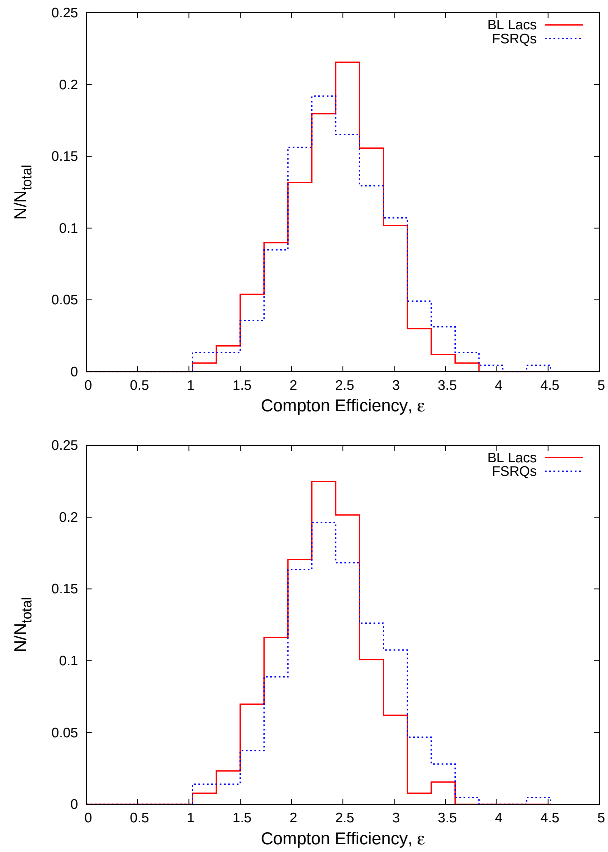

Figure 4. Top: Histogram showing the distribution of Compton efficiencies for the two populations of blazars. BL Lacs are shown in red (solid) and FSRQs are shown in blue (dashed). **Bottom:** As top panel but for sources with over 100 mJy of radio flux density.

panel of Figure 3 we show the same quantities as the top panel but with νS_ν at the peak determined by a straight line extrapolation using the given photon index and flux densities. While the two plots differ in detail, the overall trend and separation of the two populations is still evident (Spearman rank correlation coefficient $\rho = 0.513$). This implies that our results are not very sensitive to the method used to determine the peak flux density.

5.2 Compton efficiency distributions and correlations

Our primary goal has been to compare the Compton efficiencies of BL Lacs and FSRQs. There is no separation between BL Lacs and FSRQs apparent in the top panel of Figure 4 where we plot histograms of the Compton efficiencies. Application of the K-S test shows that the probability that the distributions are drawn from the same parent population is 38 per cent. Furthermore, it is clear that the Compton efficiencies of FSRQs are certainly not higher than those of BL Lacs as one might expect if the original blazar sequence hypothesis were true; the median Compton efficiencies for FSRQs and BL Lacs are $\epsilon = 2.44$ and $\epsilon = 2.47$ respectively. A Wilcoxon rank sum test on the two distributions yields the result $P = 0.51$ i.e. the null hypothesis that the medians are equal cannot be rejected at the 5 per cent level. However, we also find evidence that this result could be influenced by selection effects (see Section 6.1).

In Figure 5 we plot Compton efficiency against the synchrotron peak frequency (for the subset of our objects that have a synchrotron peak frequency provided by Abdo et al. 2010a). As stated in Section 3, in the simplest jet scenario, an increase in external photons would decrease the synchrotron peak frequency and produce a corresponding increase in gamma-ray emission, but leave the radio unaffected. Thus an anti-correlation between Compton efficiency and synchrotron peak frequency would be expected in the blazar sequence framework. This is certainly not what is observed. For the FSRQs, in all of which there is observational evidence for a copious supply of external photons, there is no indication of the expected anti-correlation, (Spearman rank test coefficient $\rho = 0.088$). Perhaps more significantly, for BL Lacs there is a positive correlation (Spearman rank test coefficient $\rho = 0.532$). Since BL Lacs are not so subject to the complications arising from the presence of a strong optical AGN we suggest that the observed correlation for these objects is a clear clue as to the physical processes occurring in SSC jets.

6 DISCUSSION

We have tried to address a fundamental question concerning blazar emission: given a certain amount of jet power, does the fraction of that power that is converted into inverse Compton emission depend on having visible AGN as a source of external photons? The main result of our analysis is the lack of any evidence that the Compton efficiencies of FSRQs are any higher than those of BL Lacs. Also,

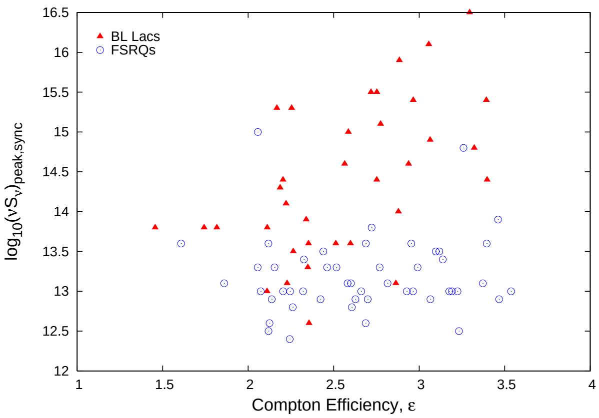

Figure 5. Synchrotron peak frequency against Compton efficiency. BL Lacs are shown by red filled triangles, and FSRQs are shown by blue unfilled circles. A positive correlation is seen for BL Lacs while there is no correlation for FSRQs.

there is no evidence for an anti-correlation of synchrotron peak frequency with Compton efficiency, which would be expected if different concentrations of external photons were responsible for shifting the peak frequency from blazar to blazar. Irrespective of the details of any blazar sequence, it is somewhat surprising that the availability of external photons to be scattered by the jet synchrotron electrons does not appear to grossly affect the overall energetics. The lack of separation between BL Lacs and FSRQs supports the view that the processes within the jets are somehow immune from outside environmental influences.

6.1 Selection effects

Before further discussion of the astrophysics we look at whether this null result could simply be a consequence of selection effects. We consider the following possibilities:

(i) *Incomplete samples.* Of the 1043 1FGL sources at $|b| > 10°$, 373 sources do not have associations with objects known at other wavelengths. Many of these could be blazars contained in the CRATES catalogue but not yet identified. If the identification process systematically excluded high Compton efficiency FSRQs and not high efficiency BL Lacs, this could bias our results.

For a gamma-ray selected sample, higher Compton efficiency goes with weaker radio emission. Since the identification process is complicated and has not been performed by ourselves we do not attempt to model its effects. We do, however, note that in Figure 2 the ratio of FSRQs to BL Lacs appears to decrease with radio flux density. For this reason we have repeated the previous analysis only using radio sources stronger than 100 mJy. The results are shown in the bottom panel of Figure 4 from which it can be seen that excluding weak radio sources reveals a difference in the Compton efficiency distributions for BL Lacs and FSRQs; the K-S test gives a probability of 2.2 per cent that the two distributions are drawn from the same parent population. Furthermore, the median Compton efficiencies are now $\epsilon = 2.33$ for BL Lacs and $\epsilon = 2.40$ for FSRQs; the Wilcoxon rank sum test rejects the null hypothesis that the medians are the same, at the 5 per cent level ($P = 0.012$). This indicates that our null result could be due to the incompleteness of our sample (especially for FSRQs) at low radio flux densities.

(ii) *Radio variability.* Most of the radio flux densities we have used in the Compton efficiency calculations were made more than a decade ago and thus radio variability will to first order increase the dispersion on the efficiency numbers. However, variability on timescales of years at 8.4 GHz is rarely by more than a factor of two. For example, Jackson et al. (2010) recently re-measured 8.4 GHz flux densities for ∼100 strong CRATES/CLASS sources and found that ⩽15 per cent had varied by more than a factor of two over that time interval. This is small compared to the more than an order of magnitude dispersion in Compton efficiencies and thus it would appear that most of the dispersion in efficiencies is intrinsic and not due to the fact that the radio and gamma-ray flux densities were not measured coevally. While it might be useful to have contemporaneous measurements, with the present limited numbers of objects it would be unlikely to affect the conclusions.

There is some evidence that selection effects arising from incompleteness at low radio flux densities may be responsible for our result that there is no separation between the Compton efficiency distributions of BL Lacs and FSRQs. Hence further work to find radio counterparts to the unidentified 1FGL sources is needed before final conclusions can be drawn from the Compton efficiency distributions. However, such selection effects do not apply our conclusions from drawn from Figure 5 where we are looking for the predicted correlation within the FSRQ population itself and fail to find it.

6.2 Compton efficiencies and the blazar sequence

The blazar sequence invokes the relative importance of a reservoir of photons external to the jet and those internally generated to account for the systematic differences in the SEDs of blazars. Another assumption underlying the blazar sequence hypothesis is that the bulk relativistic motion, particle acceleration and magnetic fields (i.e. those properties that determine the low frequency synchrotron emission) of all blazar jets have approximately the same distributions of values irrespective of whether they are hosted by BL Lacs or FSRQs. Our investigation tries to explore the consequences of such a scenario. Given the assumptions above we would expect two things:

(i) We would expect the synchrotron peak frequencies and the Compton peak frequencies for BL Lacs to be higher than those for FSRQs because of external Compton scattering. This is what is observed and is the the main theoretical justification for the blazar sequence.

(ii) We would expect a higher proportion of the energy in ultra-relativistic particles to be converted into gamma-rays in the FSRQs than the BL Lacs. The observable effect of this should be higher Compton efficiencies in FSRQs than BL Lacs and an anti-correlation between Compton efficiency and synchrotron peak frequency.

Although there is an indication that the Compton efficiencies of FSRQs are higher than for BL Lacs when taking selection effects into account, we do not see the expected anti-correlation with synchrotron peak frequency. The obvious conclusion is that some assumption underlying the blazar sequence is invalid. Either BL Lacs and FSRQs represent physically distinct populations (as indicated in the bottom panel of Figure 4) in which case our result that their Compton efficiencies are indistinguishable has to be a coincidence, or, external Compton is rarely energetically dominant.

7 SUMMARY AND CONCLUSIONS

We have defined a Compton efficiency parameter that measures the amount of energy in the jet that has been converted into inverse Compton emission. It is a more direct measure of a fundamental property of blazars than has previously been used. Based on the assumptions of the blazar sequence, we would expect the Compton efficiencies of FSRQs and BL Lacs to be different, and that an anti-correlation would exist between Compton efficiency and synchrotron peak frequency. We do not see these results in the full 1FGL *Fermi* data, although by excluding weak radio sources, we see an indication that selection effects could play a role in our results. On the other hand, based on the same assumptions we would also expect to see an anti-correlation between Compton efficiency and synchrotron peak frequency. We do not see the expected anti-correlation; this is a more robust conclusion because it is independent of possible selection biases that may affect FSRQs and BL Lacs differently. Moreover, amongst BL Lacs alone there is a positive correlation, which we suspect is a useful clue about the physics of blazar jets.

The obvious conclusion is that the availability of a source of external photons to be scattered to high energies does not have a dominant effect on the overall gamma-ray luminosities of blazars. However, it is conceivable that jets with multi-zone emission regions, possibly having different Doppler boosting factors, could account for our results. In the future larger and more completely identified samples of *Fermi*-selected sources will become available that should significantly improve the statistics and reduce selection biases.

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